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DESIGN AND IMPLEMENTATION OF LASER BEAM TO INCREASE HARDNESS OF MATERIAL

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ABSTRACT

In the present investigation, special heat treatments are used to improve the hardness of some steel alloys (20ch, 40ch and 65G), which are mainly used in the manufacturing of different types of gears in addition to aluminum- silicon alloy (AL-25), which is used in the manufacturing of piston engine named pulsed ND; glass laser of wavelength (λ = 1.06 µm, and Ƭ =300µm). Three different types of laser energies are applied to perform hardening (0.3, 0.58 and 0.93) Joule. The technique of steel alloys hardening was performed by laser transformation while laser melting was used for (AL-Si) alloy. The power densities are (1.31 * 105 to 1.1 * 106) W/cm2. The hardness obtained for (20ch) is 724Hv, 974Hv for 40ch and 1097Hv for 65G while the hardness for AL-25 was 242Hv. Depending upon the hardness before and after the process, percentage increase by 349% for 20ch, 412% for 40ch, 384% for 65G and 403% for AL-25. The hardness depth, roughness and wear were evaluated .

KEYWORDS: Gears, Heat Treatment, Laser , Steel Alloys, Hardening & Aluminum- Silicon Alloy

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Original Article

1. INTRODUCTION

There are numerous heat treatment processes to produce hardness, which reflect drastically on wear and fatigue –resistance surfaces on steel and aluminium alloys. These processes are used mainly for mechanical components which resulted in different properties of material in core and case. However, the core is normally treated to be more ductile and tougher than surface. The surface heat treatment modified by chemical treatment or by surface heat treatment to hardening and to keep the core in preheated condition. The surface treatment process explained well by [Al-Azawwi.A.K 2001]. The induction hardening heat treatment is the surface hardens of the crank shaft, cam shaft and gears. This process achieved by heating the component for a few second, and then quenching by cold water, then martensite will be formed resulted in hard outer surface and wear resistance[16]. Other simplest form of surface treatment is called flame hardening, which is achieved by four method which are mainly used in flame hardening these called as (stationary, progressive, spinning and progressive-spinning) [Rajan.T.V et.al, 1997].The electron beam hardening is used also for hardening the component by focusing the beam which is kept in vacuum pressure during the process to get heated up. Some accessories to control voltage and current like a mini computer, a work piece configuration and heating patterns for electron beam heat, such treatment are declare and investigated by [Rajan.T.V et.al, 1997].In addition to what mentioned above, the laser hardening of ferrous and nonferrous material is established widely to improve the mechanical properties of highly stressed machine parts such as gear and piston engine, which in turn increase the wear resistance of the material. The conventional and laser process are used to increase the hardness and strength in other words the phase change from austenite to martensite[1, 2, 3]. The surface hardening of aluminium silicon alloys has been the

subject of considerable interest as the simple melting of an Al-Si alloy. So, the main aims of the present investigation are by concentrating on laser hardening to get the desired mechanical properties. The laser hardening is mainly different from the previous conventional methods, but both process reached the same result as it increased the hardness. The hardness of the material will be affecting the external mechanical forces which are concentrated in the restricted area of the body[8] or it can be defined as the ability of the material to withstand scratching or indentation by another hard body, which is indicate of the wear resistance of the material[8]. The most common form of hardness tests for materials involves standard indenters being pressed into the surface of the material concerned. Measurements associated with indentation are taken as a measure of the hardness of the surface under consideration; the Brinell test, Rockwell test, the micro hardness test represented by Knoop and Vickers however, the Vickers hardness test is used in the present investigation.

2. LITERATURE REVIEW

The laser hardening was used since 1970, which is performed by CO2 lasers as it deliver enough power to the work piece, and the power density was satisfactory for hardening after that the solid state Nd:YAG was used also.Yaseen (1990) investigated the treatment hardening of carbon steel by using Nd:YAG, he found fair increasing in the hardness. Hassan (1994) studied the Nd-glass laser effect on the mechanical properties of different alloys of steel. He found different increasing in the hardness of alloys the highest one was occurred for SUS 410 others were less in hardness. In (1996) Hammodi was used pulse Nd:YAG to harden En 3 Carbone steel, he found increasing in hardness by 3.2 times the untreated sample. Ismail (1990) investigated the effect of laser hardening of AISI (1008), his investigation showed differences in the hardness and depth of the treated region. Gremaud and Kurz (1992) studied the microstructural of Al-Si alloys subjected to laser treatment using CO2. Good result was found compared to the original sample. Kadhim and Yaseen (1998) investigated the effect of the energy of higher power CW CO2 laser on surface melting niomonic-75 super alloy, and they found that the best surface melting occur with energy density about 16-40 J/mm2. Deo (2001) was studied the effect of laser hardening of eutectoid steel region by using CO2 laser, fair result was found compared to the original matrix.Purushothaman Dinesh Babu et.al (2012) investigated the effect of Nd:YAG laser in the hardening process parameters and microstructure of EN25 steel, the surface of the work piece was scanned by varying the laser beam power. They found the surface layer consist mainly martensite, in addition to increase in hardness by factor 2 times the base material hardness.Noureddine Barka and Abderra Zak El ouafi (2015). They investigated the Effects of Laser Hardening Process Parameters on Case Depth of 4340 Steel Cylindrical Specimen—A Statistical Analysis.The developed model of them exhibits good potential for converging towards a robust model able to predict the hardness curve and to generalize it for other dimensions of cylindrical parts.

3. VICKERS HARDNESS TEST

The Vickers hardness test involves a diamond indenter, in the form of square –based pyramid with an apex angle of 136^0, being pressed under load for 10 to 15 s on the surface of the material under consideration, as shown in figure 1.

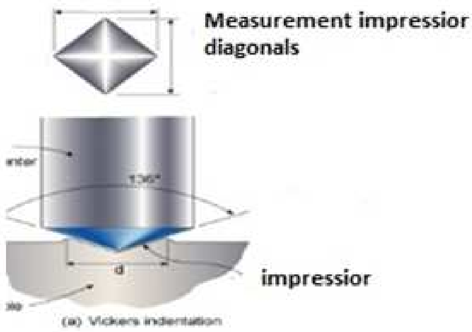

Figure 1: Vickers Hardness Test [8].

The result is a square- shaped impression. After the load and indenter is removed, the diagonals "d" of the indentation are measured. The Vickers hardness number (Hv) is obtained by dividing of the source the size of the force F, in units of Kgf, applied by the surface area, in mm2, of the indentation.

Finally, the Vickers hardness (Hv) is given by :

$$\textbf{Vickers hardness}\ \frac{\textbf{Applied force}}{\textbf{surface area of indentation}}$$

$$Hv = \frac{1.854\,F}{d^2}\,Kgf/mm^2$$

Where,

F = applied force

D = the mean diagonal of indentation (mm).

Therefore, by increasing the surface, hardness will reflect on the wear, which involves the damage of the soild surface due to the relative motion between that surface and one or more contacting substance. Six types of wear which occursduring any operation, which are mainly named abrasive adhesive, erosion, cavitation erosion, fatigue wear and fretting wear. The, most important types of wear are the abrasive and the adhesive wear, because they are take place in 65% more than the other types[8].

4. LASER MATERIAL INTERACTION

The intense pulses of laser mean thatmany potential applications which are involving heating, melting and vaporized. The laser power delivers very highpower per unit area to the desired regions of the work piece, under consideration [1]. A part of the laser radiation is absorbed and the rest is reflected, the absorbed radiation will be convert in to heat, which is very important and necessary in all surface treatment process[17].

4.1 Factors Influencing the Process of Laser Hardening

The common factors which are affecting the laser material hardening process are either related to the material parameters like and not limited, specific heat (C), thermal conductivity latent heat (K), thermal diffusivity (k), melting temperature (Tm), evaporation temperature (Tv) and specific weight. Or related to the laser parameters like wavelength (λ), mode structure, power density, focused spot size and exposure time. Figure 2 shows the physical process occur when the laser beam falls on the material surface[15]. The process involved overcoming the reflectivity and laser absorption by the material.

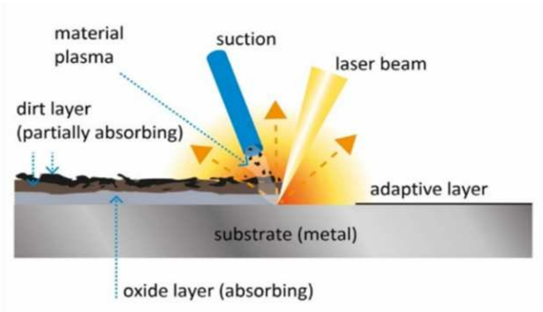

Figure 2: Physical Process Occur when the Laser Beam Falls on Material Surface [17].

The material melting by laser radiation depend drastically on the heat flow through the material, which is depend on the thermal conductivity(K) and the specific heat(c), in other word, the heating rate is inversely proportional to the specific heat per unit volume which is equal to ρc where ρ is the material density. Other important factor named thermal diffusivity(K/ρc)13, cm2/s which is represent the heat flow.The depth of heat penetration into the material for a given time (t) is[14,5].

$$D=\sqrt{4Kt} \quad (1)$$

Where:

D is penetration depth & K is the thermal conductivity.

The other material parameter, which influence the process is the material reflectivity which finally define the amount of absorbed light and the rest of reflect one, which is function of wavelength, as represented in Figure 3. The reflectivity is dimensionless number lies between zero and unity.

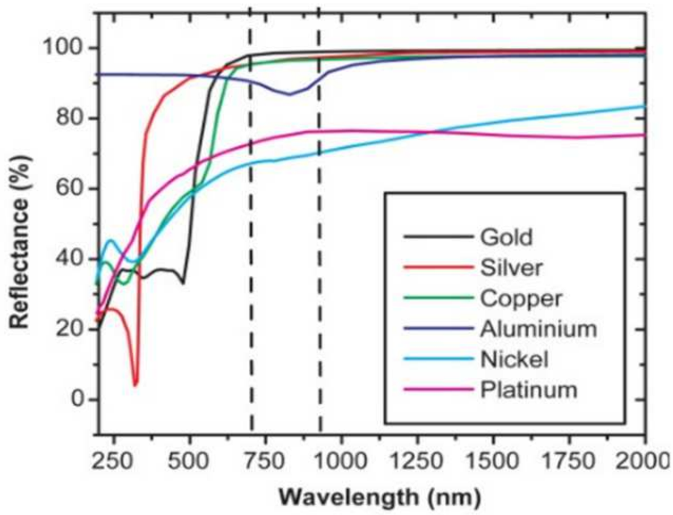

Figure 3: The Reflectivity is Dimensionless Number Lies between Zero and Unity[1] .

The relation between the reflectivity and absorptivity for an opaque material is as follows:

$$A=1-R \quad (2)$$

Where:

A is the absorptivity & R is the reflectivity.

The amount of absorbed energy mainly depends upon the optical and the thermal properties of material18.

The exponential absorption law is:

$$\mathbf{I_z=IO\ e^{-az}} \tag{3}$$

Where:

I_z is the light intensity penetrating to the depth (Z), IO is the incident light intensity and a is the absorption coefficient.The temperature will be raise at a depth Z below the surface at time t after the heat flow start19 is given by the following formula[19]:

$$\mathbf{T(z,t)} = \frac{2\,I}{K}(kt)^{1/2}\ ierfc\left(\frac{Z}{2(kt)^{\frac{1}{2}}}\right) \tag{4}$$

Where, **K** is the thermal conductivity (W/cm.OC), **(k)** is the thermal diffusivity (cm2/sec) and (ierfc) is the integral of the complementary error function. The change in surface temperature with time (Z = 0) hence ierfc(0) = 1/√π therefore, the surface temperature can be calculated simply inthe following equation:

$$\mathbf{T(0,t)} = \frac{2\,I}{K}(Kt/\pi)^{1/2} \tag{5}$$

If the melting temperature (Tm) reached as in Figure (2-b), then the time required to reach melting at the surface can be estimated from the following equation16 .

$$\mathbf{t_{m=}}\frac{\pi}{4K}\left(\frac{k\,T_m}{I_o}\right)^2 \tag{6}$$

In case of evaporation temperature (Tv), the time (tv) required to reach evaporation can be calculated by the following formula14.

tv=π/4K((k T_v)/I_o)2 (7)

When the laser is intense enough and absorbed in a certain depth, this led to high temperature opaque plasma, which is growth back along the beam of laser towered the laser source, and this called laser supported absorption wave (LSA)1, therefore most of the treatments by laser must be done below the plasma production threshold, to prevent the loss of laser energy [Rykalin.N.et.al (1988)] , they identifies the region of power density for different material.

5. LASER SURFACE TREATMENT

Heat treatment or surface hardening is one of the successful application of laser into the industrial material processing, which gives good chance of improving the characteristics of the metal parts and tools11 to give solution for any particular requirement. A summary of the main laser surface treatment is shown in figure 4.

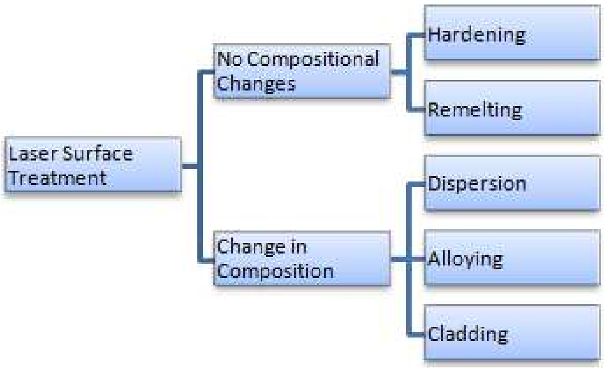

Figure 4: The Classification of Laser Surface Treatment [11].

Three important phases are indicated in the iron carbon equilibrium diagram [22].

- Ferrite (alpha phase).
- Austenite (Gamma phase).
- Cementite (iron-carbide phase).

However, The relation between the carbon and the material hardness was investigated by [Steen.W.N 1998 and Mordike.D.L (1987)].

6. THE LASER RE-MELTING OF AL-SI ALLOYS

Laser surface melting is one of the industrial interest field for materials that do not harden through martensite transformation such as cast iron, some stainless steel, titanium, tool steel and Al-Si alloys. Laser surface hardening through melting is executed by focusing beam to obtain homogenous structure due to rapid solidification rates, little thermal penetration which is resulting in little distribution[25]. Aluminum and it's alloys generally do not with stand to wear attack, one of the few exceptions case being Al-Si cast alloys, which are widely used in the car and marine engines. Oxydic surface layers and metal plating produced by electrochemical processing routs therefore have been developed for wear protection of aluminum alloys with respect to composition and microstructures, which is different from the base material. Surface modification of aluminum alloys by electron and laser beam melting has been investigated. The element aluminum can be employed as the major constituent of both the surface layer because the surface is strengthening using common metallurgical principles. Special advantage can be taken of the rapid solidification conditions by controlling heat inputscanning speed of the beam. After laser treatment, a very fine structure is developed with cell sizes in the order of few (um). Laser surface re-melting has been shown in Figure 5 to improve the wear resistance of Al-Si Alloys.

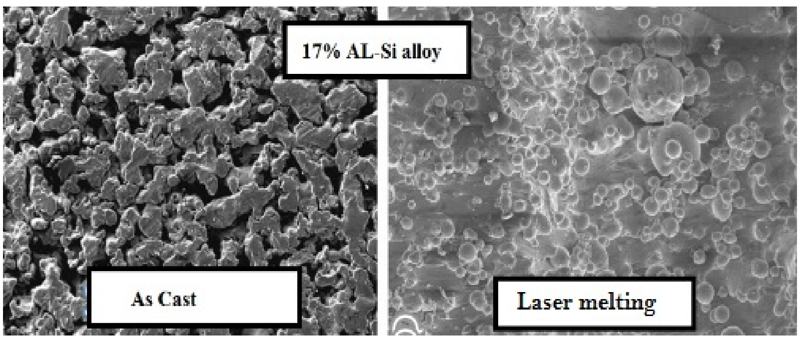

Figure 5: Laser Melting for 17% Al-Si Alloy [27].

7. EXPERIMENTAL WORK

7.1 The Proposed Laser System

Laser surface hardening needs many preparations requirements. These requirements are described in this article giving the different method employed in the present work, starting from the Nd: glass laser system that is used in this work, to instruments which depend in the examination for the treatment areas. Flow chart represented in Figure 6.

Figure 6: The Preparation and Treatments Process.

The laser system used in this work is Nd: glass laser, which is one of the most useful laser systems resulted from stimulated emission of ND ions, when these ions are presented as impurity atoms in glass. These types of lasers were developed from a laboratory tool to large operating system since 1970. Nd: glass laser operates in pulsed mode only and that is due to the lower thermal conductivity of the glass[9]. Nd: glass laser has an advantage that it can deliver high energy per pulse [100 J or more] and its cost is lower in comparison with Nd: YAG laser. The system, which is used in this work, is home made, measurement and test parameters are shown in figure 7.

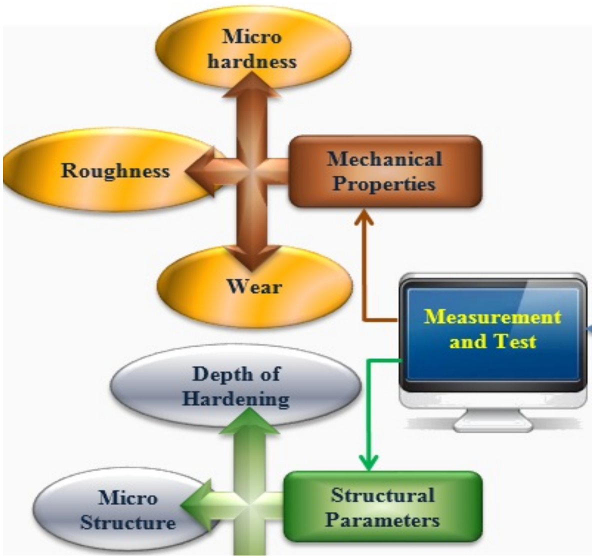

Figure 7: The Block Diagram of Measurement and Test Parameters.

The layout of system is shown in figure 8. It gives laser pulse (1060 nm) wave length and (300 µsec) pulse duration. The Nd glass rode (20 cm) in length and (2 cm) in diameter.

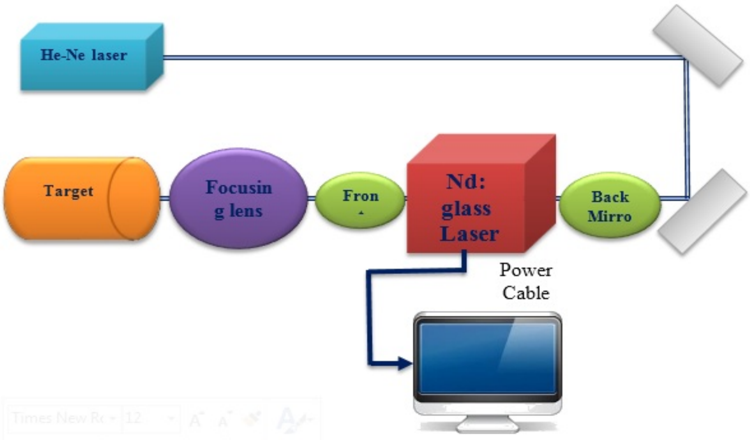

Figure 8: Block Diagram of the Experimental Setup.

The laser energy was measured using Joule meter type (ED- 200) with the aid of beam splitter method. Then, the energy of laser can be computed from the following relationship.

$$E = \frac{OSC \times SC \times 12}{10.3}$$

Where:

E = laser energy J

OSC = Oscilloscope reading

10.3 = calibration factor related to Joule-meter (ED-200) V/J12 = beam splitter ratio

The overlapping percentage can be calculated according to the following relation:

$$\%\,overlape = \left(1 - \frac{dc}{2rf}\right) \times 100\%$$

Where (rf) is the radius of spot, dc is the centre to centre spacing[26]. However, three overlapping percents have been used in this work (25%, 50%, and 75%). Micro harness test was carried out to select the suitable percentage.

8. ANALYSIS OF DATA

In the present investigation, a pulse Nd: glass was used on the surface layers of steel alloys and high silicon aluminum. The optimization measurement for laser power density, laser pulse overlapping technique and Micro-hardness test were performed. Hardness depth, wear and roughness were carried out. Figure 9 ,10 and 11 represent the relation between the measured micro hardness and laser power density with energy of 0.3 J, 0.58J and 0.93J respectively, to find the optimum value of laser power density. The power density value were selected for best distribution and minimum fluctuation.

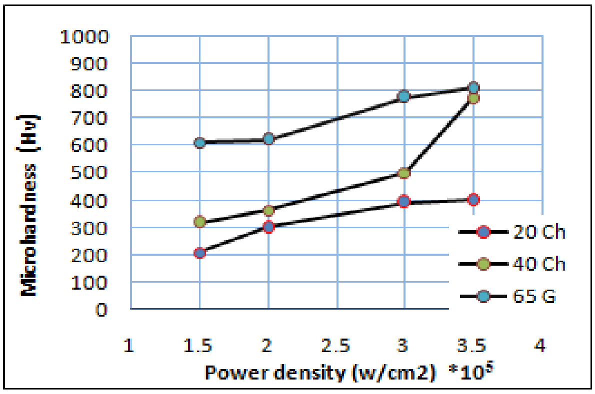

Figure 9: The Relation between the Measured Micro Hardness and Laser Power Density with Energy of 0.3 J.

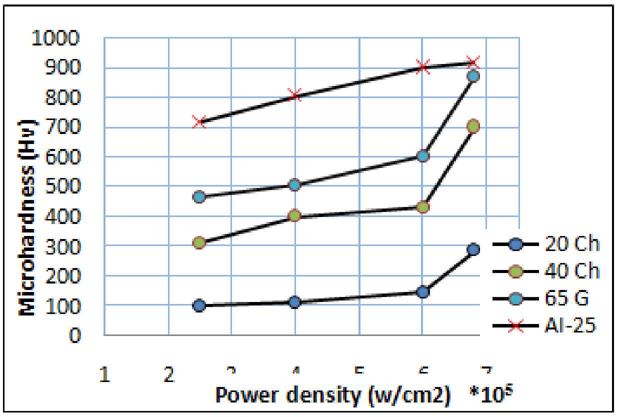

Figure 10: The Relation between the Measured Micro Hardness and Laser Power Density with Energy of 0.58J.

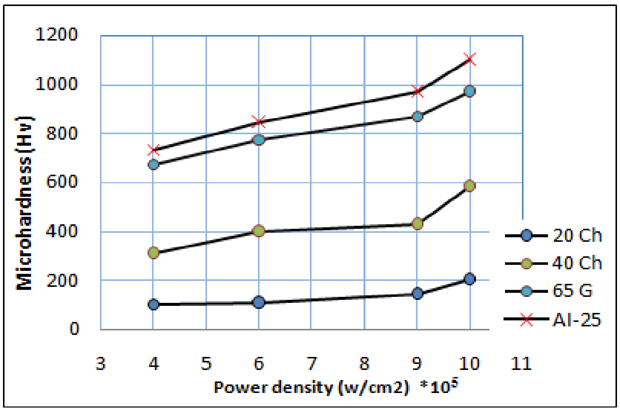

Figure 11: The Relation between the Measured Micro Hardness and Laser Power Density with Energy of 0.93J.

It is clear that the hardness increase by increasing the power density, as a result of the raising of temperature on the surface of alloy steel due to Austenite phase presentation, as the self-quenching take place according to the heat conduction. These results have an agreement with other studies [23,20,26],. Increasing of hardness of aluminum silicon alloy based on increasing the power density due to the melting of surface layer of the alloy, which in turn decrease the silicon particle size below the critical value[28].

The range of laser power densities to perform the heat treatment process were (1.31×10^5 to 1.1×10^6)w/cm2, below the lower value the effect on the subjected surface were not worthy mentioned. And, if it is more than the higher limit, then melting will take place in alloys steel while evaporating will occur in aluminum silicon alloy. Table(1) summarizes the optimumhardening number for steel alloys and Al-Si alloy before and after treatment.

Table1: Comparison of Hardening Value with Different Heat Treatment

Alloy	Before Treatment (Hv)	Mechanical Treatment (Hv)	Laser Treatment (Hv)$^{++}$
20Ch	207	633^{+}	724
40Ch	236	458	974
65 G	285	697	1097
Al 25	60	148	242

+20 Ch alloy carburized it can't have phase transformation++ At power density = 1.1×10^6 w/cm2 Figures 12,13,14, and15 represent the overlapping optimization for 20 Ch, 40 Ch, 65G and Al-25 for different overlapping ratios. The selection of optimum overlapping was made for best fluctuating and complete scanning of treatment area[2]. The best overlapping ratio was 50%, as it has equal effect of laser shots on the treated area. The hardening depth for steel alloys and aluminum silicon alloy was investigated for different laser energy (0.3 J, 0.58 J and 0.93 J).

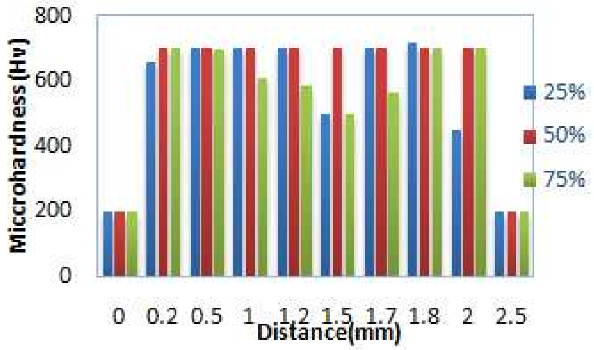

Figure 12: Overlapping Optimization for 20 ch (25%,50% 75%).

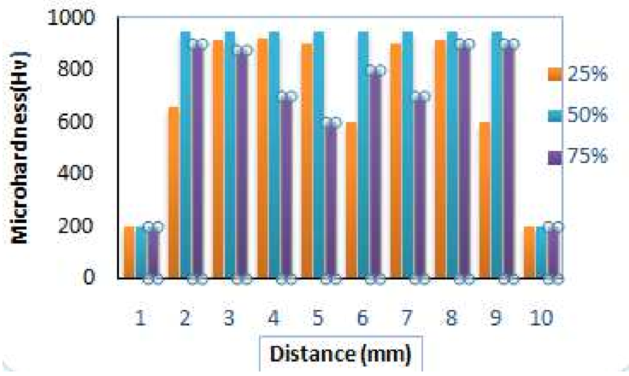

Figure 13: Overlapping Optimization for 40 ch (25%,50% 75%).

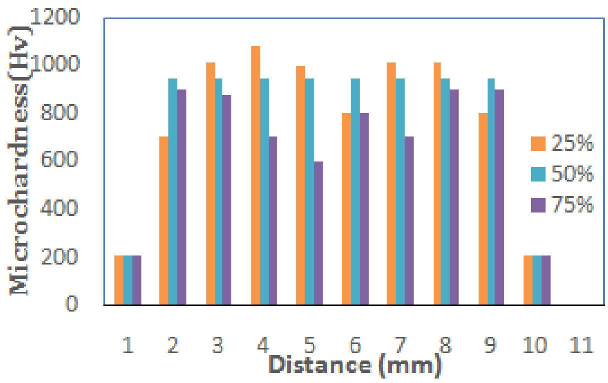

Figure 14: Overlapping Optimization for 65G (25%,50% 75%).

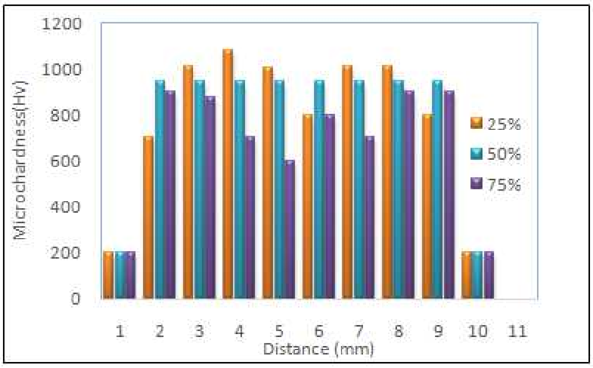

Figure 15: Overlapping Optimization for AL.25 (25%,50% 75%).

It is clear that the hardness is inversely proportional to the depth of hardening[28,29], this is due to the large temperature gradient, which varies from the first layer, which gives maximum value of hardness on the surface as it have maximum temperature gradient compared to the next layers, this result was in agreement with other researchers as show in Figure 16,17.18 .

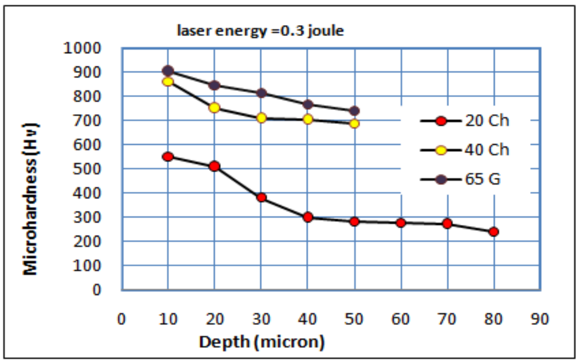

Figure 16: The Relation between Depth of Hardening and Hardness for Laser Energy 0.3J and Power Density 3.6* 10^5 W/cm^2

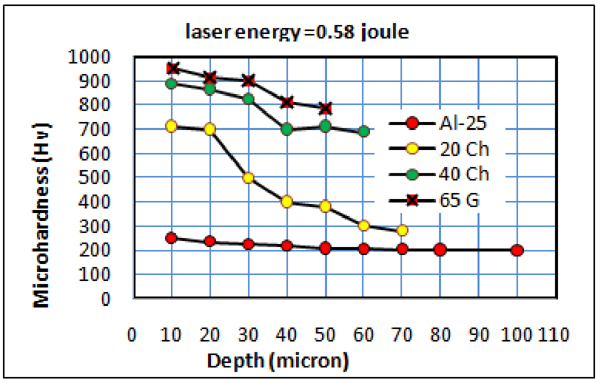

Figure 17: The Relation between Depth of Hardening and Hardness for Laser Energy 0.58J and Power Density 6.9* 10^5 W/cm^2

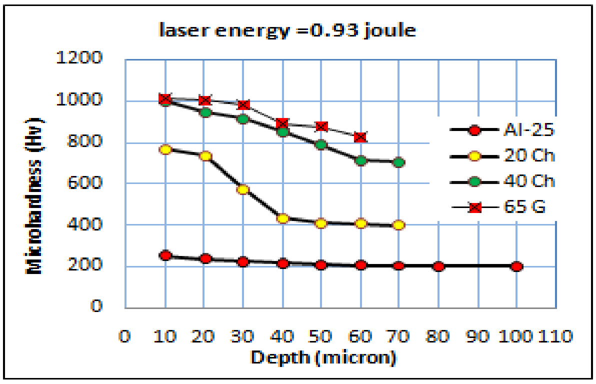

Figure 18: The Relation between Depth of Hardening and Hardness for Laser Energy 0.93J and Power Density 1.1* 10^6 W/cm^2

The surface roughness for different laser energy and power density was investigated. It shows that the roughness is directly proportional with power density, as anon uniform layers were produced due to the raising temperature[6] . The result of laser energy equal to 0.58J has been presented in Figure 19, similar trend and behavior for 0.93J and 0.3J was found. Raising in the temperature of surface leads to surface tension associated with small melting points, which gives non-uniform layers having a vary shape. Using high value of power density with short period, will lead to have nipples on the treated area and will makes the surface more rough.

Wear test was applied on the 40 Ch alloy for three conditions as follows:

- Before any treatment, the wear is 0.0557mg/m (2.3 mg/min)
- After mechanical treatment, it is 0.027mg/m (0.66 mg/min)
- After laser treatment, it is 0.0128mg/m (0.33 mg/min)

From the above results, it can be seen that the laser treatment was important in reduction of wear rate, compared to the conventional treatment due to increase in hardness that occurs in case of laser treatment to the surface of the alloy.

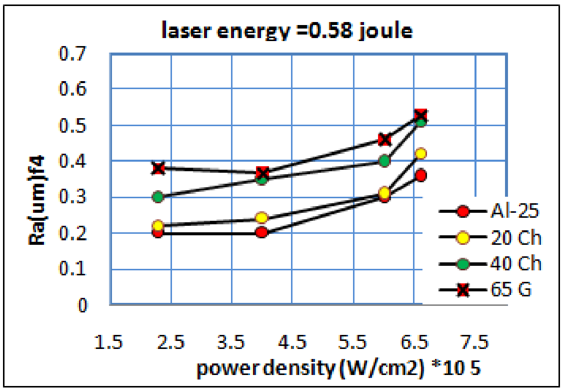

Figure 19: The Relation between Power Density and Roughness.

9. CONCLUSIONS

In this research, the following points have been concluded

- The best hardening result obtained with 0.93 J.
- There was a grain refinement processes for AL-Si alloy by laser melting.
- The marten site phase occurred in the steel alloys, after laser treatment due to rapid heating and cooling named quenching.
- Fair reduction in wear rate observed due to laser treatment.
- Nd glass laser is a high order mode of laser so; it is recommended to the treated samples to be in the focus, or near the focus of the lens, to avoid high dispersion of laser beam.
- Laser hardening does not need any post treatment for low Carbon steel alloys in the contrary of conventional method, as it needs nit riding or carburizing to increasing their hardness.
- The 50% overlapping has almost equal effect of laser shoots on the treated area.

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